Wildland fire emissions, carbon and climate:

Wildfire-climate interactions

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To be submitted to

Special issue on GHGBC from Wildland Fire Emissions

Of Forest Ecology and Management

September 16, 2012

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Abstract

Wildfires and climate are two closely related Earth system processes. Atmospheric condition has long been recognized as an environmental factor governing fires. Wildfires, in turn, impact atmospheric conditions through emissions of particles, gases, heat, and water vapor. Understanding the role of fire emissions, and how they may vary in response to expected climate change, is central to our understanding of present and future fire-climate interactions. For example, improved knowledge of the role of aerosols (including those emitted by wildfires) is currently viewed as a key to reducing remaining uncertainty in climate prediction models. Black carbon (BC) (including that emitted by wildfires) reduction has been identified as a potential climate change mitigation action. Increasing wildfire activity in recent decades, partially related to extended droughts, and concern over potential impacts of future climate change on fire activity has resulted in increased attention on fire-climate interactions. Findings from studies published in recent years have remarkably increased our understanding of fire-climate interactions and improved our capacity to delineate probable future climate change and impacts. This paper synthesizes available information on fire-climate interactions and identifies future research needs.

Smoke particles reduce overall solar radiation absorbed by the Earth's atmosphere during individual fire events and fire seasons, leading to regional climate effects including reduction in surface temperature, suppression of cloud and precipitation, and enhancement of climate anomalies such as droughts. BC in smoke particles displays some different influences affecting radiation and climate by warming the middle and lower atmosphere, leading to a more stable atmosphere. BC also plays a key role in the smoke-snow feedback mechanism. Fire emissions of CO_2, on the other hand, are an important atmospheric CO_2 source and contribute substantially to the global greenhouse effect. Fires are projected to increase in many of the global regions under a changing climate due to the greenhouse effect. Fire potential level in the U.S. is likely to increase in the Rockies and northern Great Plain all year long and in the Southeast during summer and fall seasons. Burned areas in the western U.S. could increase by more than 50% by the middle of this century. Interannual variability in area burned is found to be often related to ENSO and various teleconnection patterns. Future studies should generate a global picture of all aspects of radiative forcing by smoke particles. Better knowledge of variability in both space and time scales is needed, along with knowledge of the evolution of optical properties as smoke ages and interacts with atmospheric dynamics and cloud microphysics. Improved estimation of smoke plume height and vertical profiles and their impacts on locations of warming layers, stability structure, clouds, and smoke transport, quantified BC emission factors and optical properties from different fuels and its individual and combined roles with organic carbon are necessary knowledge components. Finally, understanding the short- and long-term greenhouse effect of fire CO_2 emissions, increased capacity to project future fire trends, especially mega-fires, with consideration of climate-fuel-human interactions, and improved fire weather and climate prediction skills, including exploring the SST-fire relations remain central knowledge needs.

Keywords: Wildfire has and PM emission, radiative forcing, feedback to climate, future fire projection

1. Introduction

Wildfires and climate are two closely related Earth system processes. Atmospheric conditions, expressed as fire weather and fire climate, are environmental factors that strongly influence fires. Fire weather includes atmospheric elements such as temperature, humidity, wind and atmospheric processes such as precipitation, fronts, jets, and troughs, and ridges. Temperature, humidity, and precipitation drive fuel moisture which is a factor for fire ignition, while wind is important for both fire ignition and spread. Fire weather determines occurrence and behavior of individual fires during specific days or months. Fire climate, meanwhile, is a synthesis of daily fire weather (Pyne et al., 1996) that describes statistical features (average, variation, etc.) of fire weather over longer time periods. Fire climate determines the atmospheric conditions for fire activity during an entire fire season, inter-fire season variability, and long-term trends.

Wildfires, in turn, can impact atmospheric conditions at various spatial and temporal scales through emissions of particles, gases, heat, and water vapor (Fig. 1). Smoke particles emitted from fires contribute to the concentration of atmospheric aerosols, which can directly affect atmospheric radiative transfer through scattering and absorbing solar radiation and indirectly through changing cloud properties as the smoke particles can serve as cloud condensation nuclei (CCN). Changes in radiative forcing lead to subsequent changes in air temperature. Additionally, CO_2 is a dominant component of fire emissions. As a greenhouse gas (GHG), CO_2 absorbs atmospheric long-wave radiation emitted from the ground and is a primary factor in global warming. Heat energy released from fires can also modify the local atmospheric thermodynamic structure, turbulence regime, and wind patterns, as well as other atmospheric thermal and dynamical properties and processes. Water vapor released from fire can increase atmospheric humidity, favoring formation of clouds and fog. The change in atmospheric conditions will in turn affect fire directly through changes in fire behavior, and indirectly by modifying fuel conditions, especially fuel moisture.

While research has historically focused on the fire–weather interactions, increasing attention has been paid in the past few decades to fire-climate interactions. A contributing factor to this emerging emphasis is the evidence that wildfires, especially catastrophic wildfires, have increased in recent decades (Piñol et al., 1998; Goldammer, 2001; Gillett et al., 2004; Reinhard et al., 2005; Westerling et al., 2006), partially related to extreme weather events such as extended droughts (Goldammer and Price, 1998; Stocks et al., 2002). Persistent weather anomalies can directly impact fire activities during a fire season. Under prolonged warm and dry conditions, fires are easier to ignite and spread and a fire season often becomes longer. Another factor is concern regarding the potential impacts of future climate change on fire activity. Many climate models have projected significant climate change during this century due to the greenhouse effect (IPCC WGI, 2007), including an overall increase in temperature worldwide and a drying trend in many subtropical and mid-latitude regions. It appears likely that wildfires will increase in these regions.

Knowledge of fire-climate interactions is essential to understanding fire and climate variability and change. First, seasonal predictions of fire risk provide invaluable aid to fire and land managers in planning fire suppression and other fire-related activities (Westerling et al., 2002; Brown et al., 2004; Roads et al., 2005). Secondly, understanding the mechanisms for seasonal atmospheric anomalies such as droughts is an extremely important climate issue with relevance beyond the fire community. Such anomalies are largely driven by interactions within the climate system such as air-sea and air-land interactions (e.g., Trenberth et al., 1988; Giorgi et al., 1996). Fire-climate interactions suggest that fire emissions are a possible external factor, which, when understood, would contribute to improving prediction skills. In addition, projection of future wildfire trends under a changing climate is essential to assess potential impacts of wildfires on human social systems and the environment and is critical to designing and implementing necessary measures to mitigate these impacts.

This section synthesizes studies on fire-climate interactions as well as fire-weather interactions. The issues to be addressed include radiative forcing of fire emissions, climatic impacts, and future trends of fires under a changing climate, and atmospheric impacts on fire behavior. These issues have been reviewed or synthesized in many studies, including Flannigan and Wotton (2001) for fire-weather/climate interactions in Canada and U.S., Kanakidou et al. (2005) and Ramanathan and Carmichael (2008) for radiative and climatic impacts of organic and black carbon, respectively, Flannigan et al. (2009) for fire and climate change, Bowman et al. (2009) for the role of fire in the Earth system, Langmann et al. (2009) for fire emissions and climatic and air quality impacts, and Hessl (2011) for climate and fire regimes. This synthesis focuses on recent radiative forcing and climatic impacts of smoke emissions, future fire trends under the changing climate, and the studies for the United States.

2. Radiative forcing of fire emissions

Incident solar radiation that drives the earth's climate system is either reflected back to space (~30%) or absorbed by the earth's surface and atmosphere (~70%). It is this absorbed radiation that heats the planet and atmosphere (Ramanathan and Feng, 2009). The overall energy budget for the planet includes not only the amount of solar radiation absorbed and reflected by the earth's surface and atmosphere, but also the amount of absorbed radiation re-emitted from the earth's surface and atmosphere as long wave radiation. Greenhouse gases and aerosols produced from wildland fires and generated in the atmosphere through chemical reactions involving precursor chemicals emitted from those fires affect the earth's overall energy balance (and thus temperature) because they also absorb and reflect long wave and solar radiation.

Smoke particles can produce radiative forcing through three mechanisms. Smoke particles emitted from fires are one of the sources of atmospheric aerosols (Andreae and Merlet, 2001). First, as with other types of atmospheric aerosols, smoke particles can impact shortwave radiation through scattering and absorbing solar radiation, a mechanism known as "direct radiative forcing" (DRF) (Charlson et al., 1992). Second, clouds are an important factor for atmospheric radiation transfer. Serving as CCNs, smoke particles can impact solar radiation by modifying the formation, structure and life time of clouds, a mechanism called indirect radiative forcing (IRF) (e.g., Twomey et al., 1984; Kaufman and Tanré, 1994). Third, the aerosol radiative forcing (both DRF and IRF) will change atmospheric structure, circulation, and energy and water exchanges on the ground surface. This will affect atmospheric water vapor and clouds, which will further affect radiation, a mechanism known as semi-direct aerosol radiative forcing (Hansen et al., 1997).

2.1 Optical properties of smoke particles

The impacts of smokes particles on radiation depend on their optical properties, mainly total optical depth (TOD) or aerosol optical depth (AOD) and single scattering albedo (SSA) (Hansen et al., 1997; Kanakidou et al., 2005). TOD is the extinction resulting from absorption and scattering of radiation by the aerosols in a column and is directly dependent on smoke particle amount. SSA is the ratio of scattering to the sum of scattering and absorption and is an indicator of intensity of absorption capacity of smoke particles. A value of unity (one) represents pure scattering smoke particles. The smaller the SSA value, the stronger smoke absorption. Smoke optical properties depend on particle size distribution and radiation wavelength.

The optical properties of smoke may differ substantially between different climate zones. (Eck et al., 2003) compared optical properties of four biomass burning events (Fig. 2). The dominant size of smoke particles increases from the tropical to temperate and to boreal sites. TOD decreases rapidly with increasing wavelength, while SSA for smoke particles that have strong absorption also decreases with wavelength. TOD is larger at the tropical sites than in the other climate zones at shorter wavelengths and smaller at longer ones (the criteria value is about 500 nanometer or nm). SSA is smaller at the tropical sites for all wavelengths. TOD of smoke particles increases with humidity (e.g., Jeong et al., 2007), a hygroscopic property.

The magnitude and variations of these two optical properties have been reported for wildfires and controlled biomass burning in a number of climate zones. The TOD of 0.75 (Ross et al., 1998) and SSA from 0.82 at 0.55 mm for young smoke and 0.94 for aged smoke (Eck et al., 1998) at about 500 nm were obtained from the Smoke, Clouds and Radiation-Brazil (SCAR-B) during the 1995 biomass burning season in Amazon. Comparable values were also obtained from the Aerosol Robotic Network (AERONET) measurements during the SAFARI 2000 dry season campaign in southern Africa (Eck et al., 2003). The maximum AOD at 550 nm ranged from 0.52 to 0.87 with SSA at 440 nm ranging from 0.92 to 0.98 were observed at a number of sites across eastern Europe, northern Scandinavia and Svalbard near Arctic (Lund Myhre et al., 2007). The mean AOD at 500 nm for April 2008 at two AERONET boreal sites in Alaska was 0.28 with maximum daily values of about 0.8 and SSA at 440 nm ranged from 0.91 to 0.99 with an average of 0.96 for observations in 2004 and 2005 (Eck et al., 2009).

2.2 Radiative forcing of smoke particles

A metric typically used to assess and compare the anthropogenic and natural drivers of climate change, including greenhouse gases, aerosols, and black carbon, is radiative forcing (Forster et al., 2007). The definition of radiative forcing as adopted by the Intergovernmental Panel on Climate Change (IPCC) is the change in net radiation (Wm^{-2}) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium (Ramaswamy et al., 2001; Forster et al., 2007).

The IPCC reports provided estimates of direct radiative forcing associated with the emissions of principal gases and aerosols (including aerosol-precursors) (Fig.3). The emissions of aerosols generally contribute to a negative radiative forcing through the scattering of solar radiation. DRF was about –0.4 and –0.24 Wm^{-2} from sulfate and organic aerosols, respectively, emitted from the period of 1750-1998 according to the third assessment report (TAR) (IPCC WGI, 2001a). Open biomass burning was assumed to account for about 75% of organic aerosol's DRF. DRF was estimated to be –0.5 ± 0.5 Wm^{-2} from of all atmospheric aerosols emitted during the period of 1750-2005 according to the IPCC fourth assessment report (FAR) (Forster et al., 2007; IPCC WG I, 2007) based on multiple studies (e.g., Hansen and Sato, 2001; Jacobson, 2001a; Hansen et al., 2002; Haywood et al., 2003; Hsu et al., 2003; Keil and Haywood, 2003; Myhre et al., 2003; Hansen and Nazarenko, 2004; Abel et al., 2005).

One of the important properties of smoke as well as other tropospheric aerosols is its large spatial variability due to the local and regional origination of fires, short periods of individual fire events, and short lifetime of particles after being emitted into the atmosphere. Measurements have shown dramatically large of wildland fire emission amounts in the Amazon and North America (e.g., Radke, 1991; Ward and Hardy, 1991; Liu, 2004) during individual fires or a burning season, making smoke an important factor to radiation budget in these regions. Biomass burning in the tropics, including tropical South America, is of particular interest because of the large extent of forest clearing and agricultural burning. More than 70% of the global burned biomass is in the tropics (Seiler and Crutzen, 1980). In addition, the large amount of incident solar radiation in the tropics enhances the radiative forcing of aerosols (Holben et al., 2001).

Penner et al. (1992) first emphasized the importance of smoke particles in the Amazon to the global radiative budget. Based on carbon emissions from biomass burning (Crutzen and Andreae, 1990; Hao et al., 1990), a globally averaged smoke DRF of about –1 Wm^{-2} was obtained, comparable to that of anthropogenic sulfate aerosols. Hobbs et al. (1997) reassessed the role of smoke from biomass burning using airborne measurements in Brazil and obtained a value that is only about one third of the early estimate. However, they pointed out that the DRF could be larger on regional scales. This result was also confirmed in (Ross et al., 1998), who obtained DRF of -15±5 Wm^{-2} for the 1995 Amazon smoke season using a one-dimensional atmospheric radiative transfer model with a total optical depth of 0.75. This magnitude is equivalent to an annually averaged DRF of about -2.5 Wm^{-2} in a typical smoke area in Brazil. Large smoke DRF was also found in Africa during the Southern African Regional Science Initiative (SAFARI2000) (Swap et al., 2003), in Southeast Asia during the 1997 forest fires (Kobayashi et al., 2004), and in the 1988 Yellowstone fires (Liu, 2005a).

The magnitude of IRF may be comparable to or even greater than that of DRF. In the IPCC FAR (IPCC 2007), the IRF of all atmospheric aerosols emitted during the period of 1750-2005 was estimated to be –0.7 Wm^{-2} with a range from –0.18 to –0.9 Wm^{-2}.

There are no estimates yet for this semi-direct radiative forcing in the IPCC reports. However, a few case studies provided some estimates of its magnitude. (Liu, 2005b) obtained a DRF of –16.5 Wm^{-2} for the smoke particles from the Amazon biomass burning simulated with a threedimensional regional climate model. The magnitude is sharply reduced to –9.8 Wm^{-2} over the smoke region when the atmospheric feedback of reduced clouds is considered. The semi-direct radiative forcing is therefore about +7 Wm^{-2}.

2.3 Black carbon

Black carbon (BC) is a product of incomplete combustion, which together with organic carbon (OC) constitutes the majority of particulate carbon. Approximately 3.3%–8.0% of fire smoke particles (by mass) are black carbon, as compared to about 50%–67% for OC. The variations can be due to different fuel types and combustion conditions, as well as the analytical methods used (Reid et al., 2005). According to (IPCC WG I, 2007), global fossil fuel emission estimates of BC at present range from 5.8 to 8.0 TgC yr^{-1} (Haywood and Boucher, 2000). Biomass burning (forest and savanna burning) contributes about 40% of total BC emissions. (Bond et al., 2004) estimated the total current global emission of BC to be 4.6 TgC yr^{-1} from fossil fuel and biofuel combustion and 3.3 TgC yr^{-1} from open biomass burning.

A special optical property of BC that differentiates it from other type of carbon is its strong absorption of solar radiation. Thus, although the overall radiative forcing of smoke particles is negative, the BC component of smoke can produce positive radiative forcing. The global radiative forcing of total BC was estimated to be +0.2 W m^{-2} in the IPCC TAR (IPCC WG I, 2001b) and up to +0.55 Wm^{-2} in IPCC FAR (IPCC WG I, 2007). (Chung et al., 2005) and (Ramanathan and Carmichael, 2008) reported a global black carbon DRF of 0.9 W m^{-2}, a value larger than the IPCC estimates and the DRF associated with other greenhouse gases such as CH_4, N_2O, or tropospheric O_3. A number of other studies (e.g. (Haywood and Ramaswamy, 1998; Jacobson, 2001b; Chung and Seinfeld, 2005; Sato et al., 2003; Bond et al., 2010) also reported large radiative forcing values between 0.4 and 1.2 W m^{-2}. On regional scales, estimates of radiative forcing due to black carbon emissions from biomass burning are rather limited. (Chung and Seinfeld, 2005) estimated a radiative forcing range of 0.52 - 0.93 W m^{-2} for the Northern Hemisphere due to black carbon emissions from fossil fuels, biofuels, and biomass burning. (Myhre et al., 2009) reported a radiative forcing range of about 0.1 to 0.7 W m^{-2} over the contiguous U.S. due to just fossil fuel and biofuel emissions.

2.4. CO_2 emissions and radiative forcing

Besides smoke particles, fire emissions also include a large amount of gases, with CO_2 accounting for 87–92% of total carbon burned (Urbanski et al., 2008). The global radiative forcing of CO_2 emitted from wildfires has been roughly estimated based on that of total atmospheric CO_2 emissions. Global carbon emissions have been estimated during the past three decades (e.g. (Seiler and Crutzen, 1980; Crutzen and Andreae, 1990; Dixon and Krankina, 1993; Hao et al., 1996; Galanter et al., 2000; Andreae and Merlet, 2001; Amiro et al., 2001; Page et al., 2002; Schultz, 2002; Duncan et al., 2003; Mouillot et al., 2006; Schultz et al., 2008; Mieville et al., 2010). The first complete estimate of averaged annual global carbon emissions was 2.6 Pg C yr^{-1} (Seiler and Crutzen, 1980). Most of recent estimates ranged from about 1.4 Pg C yr^{-1} (Ito and Penner, 2004) to 2.8 Pg C yr^{-1} (Langmann et al., 2009). (van der Werf et al., 2010) obtained an estimate of 2.0 Pg C

yr^{-1} during the period of 1997–2009 using a biogeochemical model and satellite estimates of burning information and productivity, which is about one third of total carbon emissions. This contribution could be extremely significant over a short period of time before carbon uptake resulting from regrowth of burned area vegetation. Carbon emissions during the 1997-98 Indonesian wildfires were the equivalent to the total global carbon uptake by the terrestrial biosphere in a typical year (Page et al., 2002; Tacconi et al., 2006). The contribution could be significant also over a longer period because a large portion of carbon stored in forest and other ecosystems could be lost permanently in many regions such as the Amazon region where deforestation achieved using biomass burning.

North America is one of the global regions with significant fire activity and therefore a larger contributor to global carbon emissions and radiative forcing. Carbon emission from fires in the major geographical regions or eco-regions in North America have been estimated in many studies (e.g., French et al., 2004, 2011; Amiro et al., 2001; Kasischke and Bruhwiler, 2002; Ito and Penner, 2004; Hoelzemann et al., 2004; Liu, 2004; Liu et al., 2005a; Kasischke and Johnstone, 2005; Wiedinmyer et al., 2006; Schultz et al., 2008; Reid et al., 2009; van der Werf et al., 2010) . The estimates from (van der Werf et al., 2010) are on the order of 10 Tg C yr^{-1} for continental U.S. and Mexico and 50 Tg C yr^{-1} for Canada and Alaska. In some cases at the state level, fire emissions of CO_2 can actually exceed that from fossil fuel burning in a given time period (Wiedinmyer and Neff, 2007).

According to measurements recorded at a Hawaiian observatory, atmospheric CO_2 concentrations rose from 315.98 ppmv in 1959 to 385.34 ppmv in 2008 (Keeling et al., 2009), a 22% increase over 50 years. The concentrations have increased by about 40% from about 285 ppmv in the mid-1700s. Atmospheric CO_2 can absorb long wave radiation emitted from the ground. The IPCC FAR (IPCC 2007) estimated that the radiative forcing resulting from CO_2 increases since 1750 is about 1.66 ± 0.17 W m^{-2}. The large ratio of fire to total carbon emissions suggests a significant contribution of fire to total CO_2 radiative forcing.

3. Climatic impacts

3.1 Smoke particles

3.1.1 Atmospheric thermal structure and circulations

Solar radiation is the ultimate energy source for the atmosphere and one of the energy balance components that determine atmospheric thermal structure. While the impact of GHG (including those from fire emissions) increases on atmospheric warming has been effectively determined for some time, the impact of aerosols (including those from fire emissions) has been more difficult to quantify. Aerosol radiative forcing impacts, direct and indirect, demonstrate significant variability in space and time, with current estimates indicating negative forcing for both aerosol direct and indirect (cloud albedo) forcing (Quaas et al., 2008). Estimates are that anthropogenic aerosols (air pollution) have overall lessened the warming impacts resulting from GHG increases and have had a significant impact on critical ocean-atmosphere interactions that drive important cycles of atmospheric variability (Evan et al., 2011; Booth et al., 2012; Evan, 2012). Radiative forcing of smoke particles is negative when smoke particles are locally present in sufficient density in the atmosphere, meaning that radiation absorbed by the earth-atmosphere system becomes smaller, the ground surface will experience cooling. This was observed during a wildfire near Boulder, Colorado in 2010 (Stone et al., 2011) where the surface under the smoke plume was cooled by 2°–5°C. To the contrary, smoke can increasing surface warming by impacting cloud formation and I smoke particle absorption of solar radiation (Fig. 4) (Feingold et al., 2005). The net change in air temperature depends on the relative importance of the absorption and the change in sensible heat flux on the ground surface related to the reduction in solar radiation absorbed solar radiation due to smoke particles (Liu, 2005b). The lower and middle troposphere becomes more thermally stable. The net cooling effect of smoke particles may have implications for climate change. Smoke transported from wildfires in northern boreal forests to the Arctic could cool the Arctic for weeks to months at a time, temporarily countering warming due to the greenhouse effect (Stone et al., 2008).

The change in atmospheric thermal structure due to the direct radiative forcing of smoke particles can further change regional circulations (Evan et al., 2011; Booth et al., 2012). Simulations (e.g., Liu et al., 2005; Liu, 2005b) showed that smoke particles emitted during a biomass burning season in South America increases 500 hPa geopotential heights over the smoke region, indicating a tendency of enhanced Atlantic Ocean high or weakened tropical trough. This tendency could last into post-burn period, implying a delay of monsoon onset or weakening of its intensity.

3.1.2 Clouds and precipitation

Clouds and precipitation are usually reduced in the presence of smoke particles. Different physical mechanisms have been proposed for this reduction. During the Indian Ocean Experiment (INDOEX) there was relatively small cloud coverage over the ocean area due to the large concentration of soot (a substance consisting of BC and light absorptive carbon or brown carbon) aerosols, which absorb solar radiation, increase air temperature, reduce relative humidity, and therefore "burn out" clouds (Ackerman et al., 2000). Cloud and precipitation reductions due to smoke over the Amazon were found mainly as a result of smaller water vapor transport from the ground and the planetary boundary layer to the cloud layer due to the combined effects of reduced turbulent activity and the subsidence tendency (Liu, 2005b). For the intense wildfires during the 2004 Alaska fire season, the high concentrations of fine aerosol ($PM_{2.5}$) and the resulting large numbers of CCN had a strong impact on cloud microphysics when clouds were present, with decreased or increased precipitation, depending on the time into model simulation employed (Grell et al., 2011). The cloud impact of smoke also depends on intensity of smoke radiative forcing (Ten Hoeve et al. 2012). With increasing AOD, cloud optical depth (COD) was found to decrease at higher AODs, but increase at lower AODs. Field measurement provided observational evidence for cloud changes directly related to biomass burning in the Amazon region (Koren et al., 2004; Andreae et al., 2004). (Koren et al., 2004) analyzed the satellite measurements from Moderate Resolution Imaging Spectroradiometer (MODIS) during the biomass burning season and found that clouds were reduced from 38% in clean conditions to 0% for heavy smoke (Fig. 5).

3.1.3 Seasonal climate anomalies

For long duration fire seasons that often are associated with droughts, the impacts of smoke particles on radiation and precipitation can last for several months and therefore may reinforce seasonal climate anomalies. Liu (2005a) simulated the role of the Yellowstone fires in the development of the 1988 northern U.S. drought using a regional climate model. The precipitation perturbation in response to radiative forcing of smoke aerosols is mostly negative in the Northwest, with the largest reduction of about -30 mm in the northeastern Midwest. The simulated perturbation pattern is similar to the observed pattern of precipitation anomalies, suggesting that the smoke particles might have enhanced the drought (Fig. 6). Tosca et al. (2010) investigated the interactions between equatorial Asian fires and ENSO-induced regional drought using satellite observations and atmospheric modeling of several types of smoke affected radiative forcing and precipitation variations. They found that the combination of decreased SSTs and increased atmospheric heating reduced regional precipitation. The vulnerability of ecosystems to fire was enhanced because the decreases in precipitation exceeded those for evapotranspiration. The results imply a possible positive feedback loop in which anthropogenic burning in regionally intensified drought stress during El Nino.

3.2 Black carbon-snow interactions

BC emissions enhance the greenhouse effect in the atmosphere, which is mainly caused by the increased atmospheric CO_2 concentration. Due to the strong solar radiation absorption capacity and high concentrations tropical latitudes where solar irradiance is highest, black carbon emissions are considered to be the second strongest contributor to current global warming, after carbon dioxide emissions (Ramanathan and Carmichael, 2008). According to their estimate, the radiative forcing of BC would have a globally averaged surface warming effect of 0.5 - 1.0°C. The role of BC in climate change was emphasized in the recent EPA's report on BC to Congress (EPA, 2012).

A special role of BC in climate variability and change is related BC-snow interactions. The deposition of BC transported from other parts of the world on snow and ice covers in high latitudes reduces albedo and increases solar radiation absorbed by the ground, which in turn speeds up snow melting (Hansen and Nazarenko, 2004). Boreal fires contribute more BC to the Arctic than anthropogenic sources in summer based on multiyear averages (Stohl et al., 2006). A case study of extensive boreal fires in Russia during 2003 estimated they contributed 50% of the BC deposited north of 75N in spring and summer and were a big factor for local haze (Fig. 7) (Generoso et al., 2007). Flanner et al. (2007) calculated global annual mean BC/snow surface radiative forcing of +0.054 and +0.049 Wm^{-2} for a strong and a weak boreal fire year, respectively, with about a 20% contribution from biomass burning. Global land and sea-ice snowpack absorbed 0.60 and 0.23Wm^{-2}, respectively, because of direct BC/snow forcing in the strong fire year.

3.3 Greenhouse effects of CO_2 emissions

Greenhouse effects and related climate change with the increased atmospheric CO_2 concentrations have been extensively assessed in the IPCC reports (IPCC WG I, 2001b, 2007), which basically indicate warming worldwide, overall drying in many subtropical and mid-latitude regions, and more frequent and intense climate anomalies. This provides some essential information for assessing the climatic effects of fire emissions, which are one of the important sources for atmospheric CO_2.

4. Future fire trends under a changing climate

4.1 Fire potential and risk

Fire potential and risk indices are measures of the possibility of fires of a certain severity occurring in an area. Fire risk indices are often analyzed and projected using fire weather based indices and atmospheric and oceanic patterns that are associated with severe wildfire occurrence. Future fire potential trends can be projected by comparing their values between now and future. Most often used fire indices include the Keetch-Byram Drought Index (KBDI) (Keetch and Byram, 1968), Fire Weather Index (FWI) (Van Wagner, 1987), the Fosberg Fire Weather Index and its modified version (Fosberg, 1978; Goodrick, 2002), and Australian McArthur Forest Fire Danger Index Canadian (Luke and McArthur, 1978), .energy release component (ERC), burning index (BI), etc. They are parts of fire danger rating systems such as the U.S. National Fire Danger Rating System (NFDRS) (Deeming et al., 1977; Burgan, 1988) and the Canadian Forest Fire Danger Rating System (CFFDRS). The atmospheric and oceanic patterns associated with fires vary by region and include phenomena such as the breakdown of a blocking ridge and climate patterns such as ENSO, the Pacific Decadal Oscillation (PDO), the Pacific North American pattern (PNA) and the Atlantic Multidecadal Oscillation (AMO).

A number of studies have provided more details about future North American and global fire trends using fire indices derived from regional or local climate change scenarios downscaled statistically or dynamically from GCM projections. Heilman et al. (1998) suggested the future occurrence of more surface pressure and atmospheric circulation patterns that are associated with severe wildfire occurrence in the eastern and southeastern U.S. Flannigan et al. (2001) used the FWI to show that future forest fire danger is expected to increase across most of Canada. Brown et al. (2004) projected fire danger for the western U.S based on ERC. The number of days of high fire danger is expected to increase by the end of this century mainly in the northern Rockies, Great Basin and the Southwest – regions that have already experienced significant fire activity this century. Wotton and Martell (2005) projected an increase in lightning fire activity of 80% by the end of the 21st century. Liu et al. (2009, 2012) projected global and U.S. fire potential using the KBDI for future climate projections from four GCMs under various emissions scenarios. This study projected increases in fire potential for western North America, southern Europe, central Asia, and central South America, central South Africa, and parts of Australia. For the U.S. (Fig. 8), future fire potential will increase significantly in the Rocky Mountains for all seasons and in the Southeast and Pacific coast during summer and fall, with an exception in the inter-Mountain region where KBDI decreases in winter and spring. The increase in KBDI is more than 100 in many regions, which could be large enough to change fire potential level from low to moderate or from moderate to high.

4. 2 Fire properties

Actual fire properties such as burned area, occurrence, intensity, severity, and seasonality have been projected using their statistical relationships with climate conditions and empirical relations based on historical climate and fire data. Climate data usually include atmospheric elements such as temperature, humidity, precipitation and lightning, and fire indices. Fuel conditions and human activity are also useful factors in addition to climate conditions. The most popular statistical relations are correlations or regressions between fire and climate at specific locations.

Several fire probability models were developed recently. For example, Arora and Boer (2005) predict probability of fire occurrence based on probabilities of fire related to biomass, moisture, and ignition (both lightning and human causes). Fire spread is dependent on wind direction and speed. Fire duration (extinguishing) is related to natural barriers and fire suppression. Preisler and Westerling (2007) use a two-step method to estimate probability of certain large burned area for a given 1-degree grid cell during a given month: probability of occurrence of at least one fire (ignition), and probability of fire spread or escape. Logistic regression with piecewise polynomials is used with factors including monthly temperature, Palmer Drought Severity Index, and SST anomalies. Pechony and Shindell (2009) estimate fire counts per month per unit square kilometer based on flammability (determined by vapor pressure, temperature, and precipitation, and vegetation), ignition, and suppression.Ignition due to both lightning and human causes are considered. Cloud-to-ground flash rate are estimated using the 4th order polynominal regression with atmospheric thermal and microphysics parameters (such as CAPE and UMF). The regression relations are evaluated using the LIS/OTD measurements (Christian et al., 2003). The human factor (including suppression) uses population density as a major parameter (Pechony and Shindell, 2009).

Many studies project overall increases in burned area in boreal regions, but with varying magnitudes among the various studies (e.g., Amiro et al., 2001; Flannigan et al., 2005; Balshi et al., 2009). An increase of 74–118% by the end of this century was obtained in a tripled CO_2 scenario (Flannigan et al., 2005). Liu et al. (2005) estimated an increase of 50% for the U.S. average and over 100% for the western U.S. by 2050. Spracklen et al. (2009) showed that increases in temperature cause annual mean area burned in the western United States to increase (Fig. 9), on average by 54% by the 2050s relative to the present day. Krawchuk et al. (2009) used statistical generalized additive models (GAMs) to characterize current global fire patterns and project the potential distribution of fire in the 21st century based on fire, climate, net primary productivity, and ignition data. Using empirical relations between fire activity and parameters including vegetation density, ambient meteorological conditions, availability of ignition sources, and fire suppression rates to project global fire trends based on the simulated climate variations and land-use changes. Pechony and Shindell (2010) projected a shift to a temperature-driven global fire regime in the 21st century, resulting in a more fire-prone global environment.

4.3 Vegetation changes and fire impacts

Fuel is another environmental factor for fire. Fuel conditions such as moisture and loading can significantly impact fire behavior and properties. Fuel conditions are expected change as well under a changing climate (e.g., Zhang et al., 2009). Also, change and/or shift from a species type to another at a specific location can happen under a changing climate. Thus, climate change can impact fires indirectly through changing fuel conditions and vegetation types. Vegetation models including global dynamic vegetation models (GDVMs) have been used to predict future vegetation conditions and related fire change. GDVMs are highly integrated process-based terrestrial ecosystem models that simulate daily or monthly carbon, water and nitrogen cycles driven by the changes in atmospheric chemistry including ozone, nitrogen deposition, CO_2 concentration, climate, land-use and land-cover types and disturbances. GDVMs usually include four core components of biophysics, plant physiology, soil biogeochemistry, and dynamic vegetation and land-use. The examples of DGVMs include HYBRIDS (Friend et al., 1997), MC1 (Bachelet, Lenihan, et al., 2001), LPJ (Sitch et al., 2003), CLM (Levis et al., 2004), IBIS (Foley et al., 2005), DLEM (Tian et al., 2010).

Fire is one of the disturbances included in these models. It is described either as an internal process or an external forcing. As an internal process, it could change due to climate change which is expressed as varied boundary conditions of both atmospheric CO_2 and meteorological conditions (radiation, temperature, humidity, precipitation, etc.). The fire module in MC1 (Lenihan et al., 1998) simulates the occurrence, behavior, and effects of fire. The module consists of several mechanistic fire behavior and effect functions (Rothermel, 1972; Peterson and Ryan, 1986; Van

Wagner, 1993; Keane et al., 1997) embedded in a structure that provides two-way interactions with the biogeography and biogeochemistry modules. The rate of fire spread and fire line intensity are the model estimates of fire behavior used to simulate fire occurrence and effects. The occurrence of a fire event is triggered by thresholds of fire spread, fine fuel flammability, and coarse woody fuel moisture.

Future changes in vegetation and fires were projected with MC1 for the U.S., especially western U.S. and Alaska (Aber et al., 2001; Bachelet, Lenihan, et al., 2001; Bachelet et al., 2005; Lenihan et al., 2003; Whitlock et al., 2003; Rogers et al., 2011). The simulated vegetation distribution Bachelet et al. (2001) is dominated by broadleaf forest in Florida, Southeast mixed forest in the Gulf coast from east Texas to South Carolina, temperate deciduous forest in rest of Southeast, Northeast mixed forest in Northeast, and grassland/ savanna / woodland in eastern Midwest. Future projection indicates extension of Northeast mixed forest to eastern Midwest with HadCM climate change scenario, and northward immigration of various forests for CGCM. Most significant changes in western U.S. are disappearance of taiga/tundra in Northwest and northern Rockies and replacement of many arid lands by grassland in Southwest. The projected changes in regional vegetation patterns would significantly alter the occurrence and distribution of wildfires. The average annual acreage and biomass burned across the U.S. is estimated to increase (Bachelet et al., 2003). By the end of the 21st century, 75%–90% of the area simulated as tundra in Alaska in 1922 is replaced by boreal and temperate forest (Fig. 10).

Scholze et al. (2006) estimated changes in global ecosystem processes due to climate change during the 21st century. Simulations with LPJ using multiple climate change scenarios show forest shifts and change in wildfire frequency, with high risk of forest loss for Eurasia, eastern China, Canada, Central America, and Amazonia and forest extensions into the Arctic and semiarid savannas. More frequent wildfire will appear in Amazonia, the far north, and many semiarid regions. Gonzalez et al. (2010) classified global areas into vulnerability classes by examining the changes of ecosystems in response to observed changes of 20th century climate and to projected 21st-century vegetation changes using MC1. Temperate mixed forest, boreal conifer and tundra and alpine biomes were found to have the highest vulnerability, often due to potential changes in wildfire. In addition to the global regions indicated above, wildfire is expected to increase in southeastern U.S., southeastern and northern China, and northern India.

5. Fire-atmosphere interactions

5.1 Atmospheric conditions and processes for fire behavior

As the previous sections have pointed out, wildland fires are capable of altering local weather and climate conditions. However, these changed atmospheric conditions also feedback upon fires. Werth et al. (2011) provides a thorough review of critical fire weather patterns associated with extreme fire behavior. These critical patterns act to bring into alignment the important weather elements for destructive wildfires: hot, dry, and windy conditions. The role of particulate emissions from fires influencing cloud properties and altering precipitation patterns provides the most direct link to hot and dry conditions through reduced cloud cover and rainfall amounts. The impact of changes in either surface temperature or the vertical profile of temperature is not as simple.

Changes in surface air temperature are not a primary driver of fire behavior on their own, but rather act through changes to fuel moisture. Assuming the moisture content of the air remains constant, an increase in temperature results in decreases in fuel moisture and therefore enhanced fire behavior. Shading from a smoke plume can reduce surface temperatures, thereby increasing fuel moisture levels and suppressing the fire behavior. Other areas not directly shaded by the smoke column often experience reduced cloud cover and therefore receive more incoming solar radiation at the surface which increases the surface temperature. The Greenhouse Gas component of wildfire smoke's impact on the climate system suggests that surface temperatures would be warmer, leading one to expect reduced fuel moistures and enhanced fire behavior. However, warmer global temperatures also imply increased evaporation from the oceans adding moisture to the lower levels of the atmosphere and perhaps increasing cloud cover which makes estimating the impact of Greenhouse Gas induced warming on fire behavior difficult. Warming at upper levels of the troposphere due to the absorption of solar radiation by smoke particles will act to make the atmosphere more stable. While stable atmospheric conditions are not favorable for extreme fire behavior in most cases, these conditions are favorable for cloud free conditions which generally support the requirements of a hot and dry environment.

5.2 Teleconnection and seasonal fire activity

Certain climatic patterns are strongly associated with prolonged periods of hot, dry and windy conditions favorable for wildfire occurrence and spread. The El Nino Southern Oscillation (ENSO) is perhaps the best known climatic pattern impacting conditions across the United States. There are several other modes of climate variability that can significantly influence regional climate. Teleconnection patterns are modes of atmospheric variability often revealed through empirical orthogonal function (EOF) analysis of geopotential heights and describe how different parts of the globe are connected through the climate system. The relative importance of each teleconnection pattern typically varies with season, as some are dominant in the winter whereas others may dominate during the summer. The influences of several teleconnection patterns manifest themselves by either enhancing or mitigating the impact of ENSO.

Studies on fire–climate relationships have revealed complex relationships that depend on the interaction of several teleconnection indices. For the western U.S., prime conditions for wildfires occur when abnormally wet years are immediately followed by drought; conditions favors as ENSO transitions from positive to negative phase (Swetnam and Betancourt, 1998; Kitzberger et al., 2001; Norman and Taylor, 2003). In the southeastern U.S., ENSO is also a dominant factor influencing wildfires, but here it is just the dry conditions favored by the negative phase of ENSO are critical as vegetation is abundant most years due to the generally moister conditions (Simard et al., 1985; Brenner, 1991). Heilman (1995) employed EOF analysis to identify atmospheric circulation patterns that were prevalent at the onset of severe wildfires across the United States. The two leading modes of this analysis represented the positive and negative phases of the Pacific–North American teleconnection pattern (PNA). Liu (2006) identified the closely coupled spatial patterns between pacific SST anomalies and intense U.S. Fires using the singular value decomposition technique. Goodrick and Hanley (2009) provided evidence that the fire conditions in Florida were more complex than described by (Brenner, 1991) as interactions between ENSO and the PNA explain more of the variability in area burned than either climate pattern alone (Fig.11). Dixon et al. (2008) reveal an even more complicated set of interactions in their investigation into Mississippi's wildfire activity that includes ENSO and the PNA as well as the Pacific Decadal and North Atlantic Oscillations (PDO and NAO respectively).

6. Conclusions and discussion

This chapter has reviewed many of the recent studies on fire and climate interactions from the past few decades. The major findings from these studies include:

a. Wildfire emissions can have remarkable impacts on radiative forcing. Smoke particles reduce overall solar radiation absorbed by the earth-atmosphere at local and/or regional scales during individual fire events or burning seasons. Fire emissions of CO_2, on the other hand, are one of the important atmospheric CO_2 sources and contribute substantially to the global greenhouse effect.

b. The radiative forcing of smoke particles can generate significant regional climate effects. It leads to reduction in surface temperature. Smoke particles mostly suppress cloud and precipitation. Fire events could enhance climate anomalies such as droughts.

c. Black carbon in smoke particles plays some different roles in affecting radiation and climate. BC could lead to warming in the middle and lower atmosphere, leading to a more stable atmosphere. BC also plays a key role in the smoke-snow feedback mechanism.

d. Fires are expected to increase in many regions of the globe under a changing climate due to the greenhouse effect. Fire potential levels in the U.S. are likely to increase in the Rockies all year long and in the Southeast during summer and fall seasons. Burned areas in the western U.S. could increase by more than 50% by the middle of this century.

e. Interannual variability in area burned is often related to ENSO and various teleconnection patterns. Unfortunately, climate models are limited in their ability to provide information on potential changes regarding ENSO variability and its interaction with various teleconnections in North America which limits our ability to discuss future shifts in fire potential beyond just changes in the mean potential. However， the models are improving in this area and useful seasonal to multi-year projections of ENSO, AMO etc are probable in the next few years, which will improve prediction of interannual fire variability.

Many issues remain, which lead to uncertainties in our understanding of fire-climate interactions. Further studies are needed to begin to reduce these uncertainties. For fire particle emissions, a global picture of all kinds of radiative forcing is needed. It is a challenge considering the significant variability in both space and time scales that characterize smoke emissions, along with the evolution of optical properties as smoke ages, and interactions with atmospheric dynamics and cloud microphysics. Smoke plume height and vertical profiles are important properties for smoke particles' impacts on the atmosphere, including locations of warming layers, stability structure, clouds, and smoke transport. Many simulation studies have been conducted based on assumed profiles. Some recent techniques such as the Multi-angle Imaging SpectroRadiometer (MISR) (e.g., Kahn et al., 2008) could be useful tools to determine these smoke plume properties. BC has received increased attention recently. BC emissions from fires, including emission factor from different fuels need to be improved. In addition, BC and OC have different optical properties and climate effects. New techniques for measurement, analysis, and modeling are required to help investigate their separate and combined roles.

Work remains to be done on the assessment of the greenhouse effects and climate change deriving from fire CO_2 emissions.. Unlike atmospheric total CO_2 concentrations, which have increased relatively steadily since the industrial revolution, fires have significant temporal variability. Fire regimes of a specific region may change dramatically, as a result of changes in both climate and human activities. The variability can occur also over a short period. For example, the global carbon emissions in 1998 were 0.8 Pg yr^{-1} more than the average, but by 2001 they had dropped to 0.4 Pg yr^{-1} below the average (van der Werf et al., 2010). Thus, it is hard to estimate historical fire CO_2 emissions and their impacts. Furthermore, the contribution of wildfire emissions to global atmospheric CO_2 increase is more significant over a short period because regrowth of burned lands over a long period will remove some CO_2 from the atmosphere.

For future fire trend projection, wildfires occur at local or regional scale, while current climate models do not have the capacity to provide consistent and reliable simulation of climate variability at these scales, in particular for precipitation. Under the projected warming climate, the risk from mega-fires, which are small probability events and involve complex atmospheric, fuel, and human processes, would become larger. Many statistical climate-fire relations and vegetation models have very limited prediction skills for mega-fires. Fuel conditions such as type, loading and moisture could change at a specific location in response to climate change. They will be also affected by human factors such as urbanization. Comprehensive approaches combining natural and social factors are needed for improving future fire projections.

While the strong relationships between atmospheric teleconnection / SST patterns and wildfire activity are useful for seasonal forecasting applications, there application to climate change scenarios is problematic. Joseph and Nigam (2006) revealed that the climate models used in the IPCC's Fourth Assessment report currently do a poor job simulating many features of ENSO variability and its interaction with various teleconnections in North America. ENSO-fire relations are valuable for seasonal fire predictions. USDA Forest Service and U.S. National Oceanic and Atmospheric Administration joined research forces recently to develop plans and tools to improve fire weather and climate prediction skills, including exploring the SST-fire relations.

Acknowledgements This study is part of a synthesis project on greenhouse gases and aerosols from wildland emissions, the USDA Forest Service Research and Development. The authors would like to thank the support from the FS Southern Research Station and the Northern Research Station. The editing and comments provided by Bill Sommers, Sue Conard, and Stanley Coloff of George Mason University are appreciated. The study is partially supported by the USDA/USDI Joint Fire Science Program project under Agreement No. JFSP 11172.

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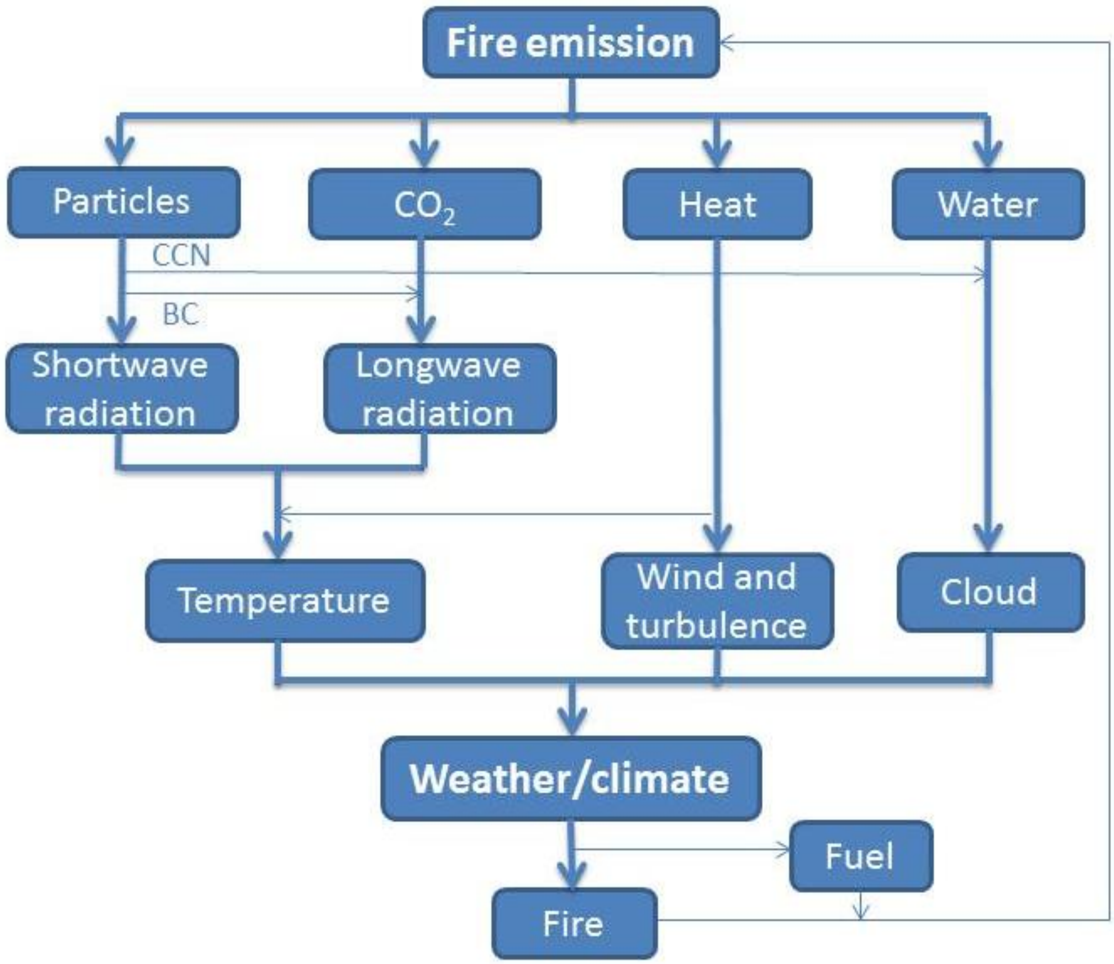

Figure 1 Diagram of physical processes for fire' impacts on weather and climate.

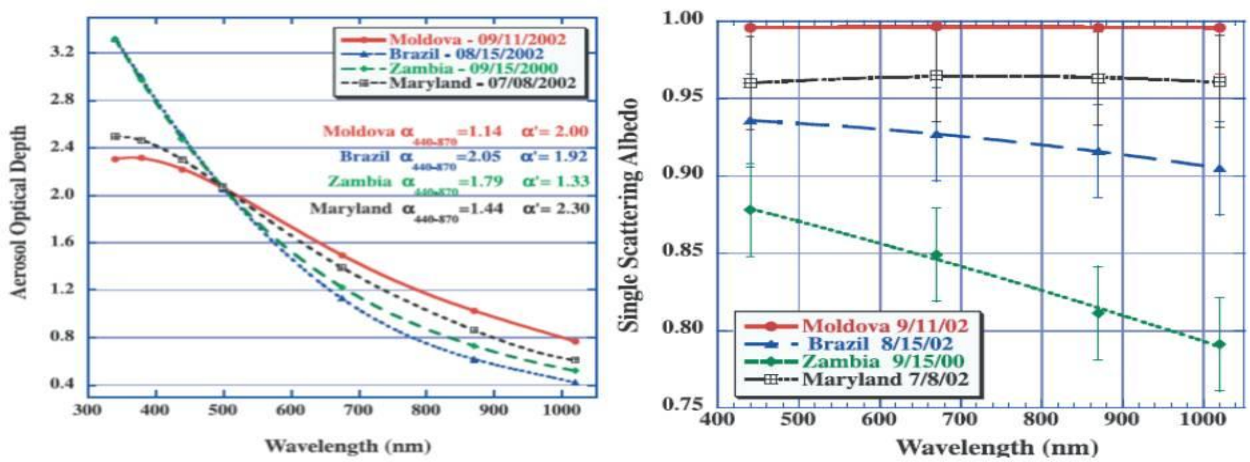

Figure 2 Distributions of aerosol optical depth (left) and single scattering albedo (right) with spectra for four smoke events (from Eck et al. 2003).

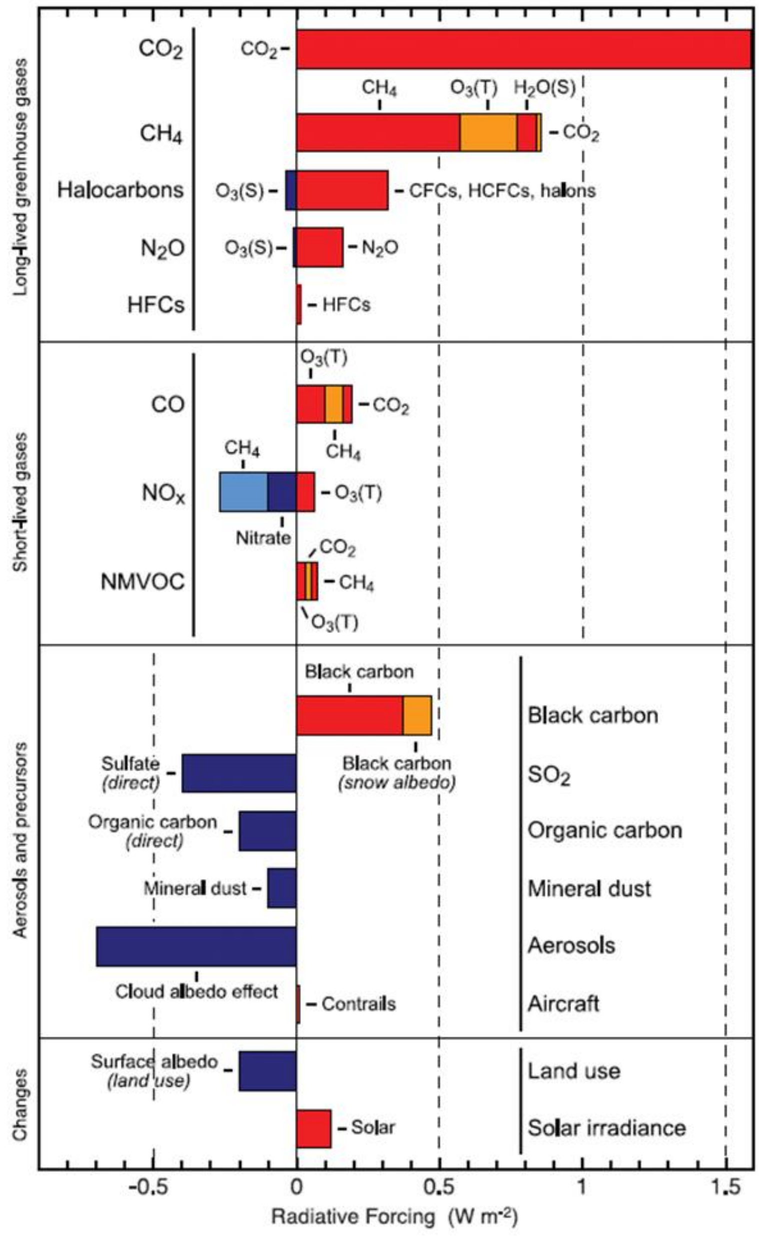

Figure 3 Radiative forcing for emissions of principal gases, aerosols and aerosol precursors. (from IPCC 2007).

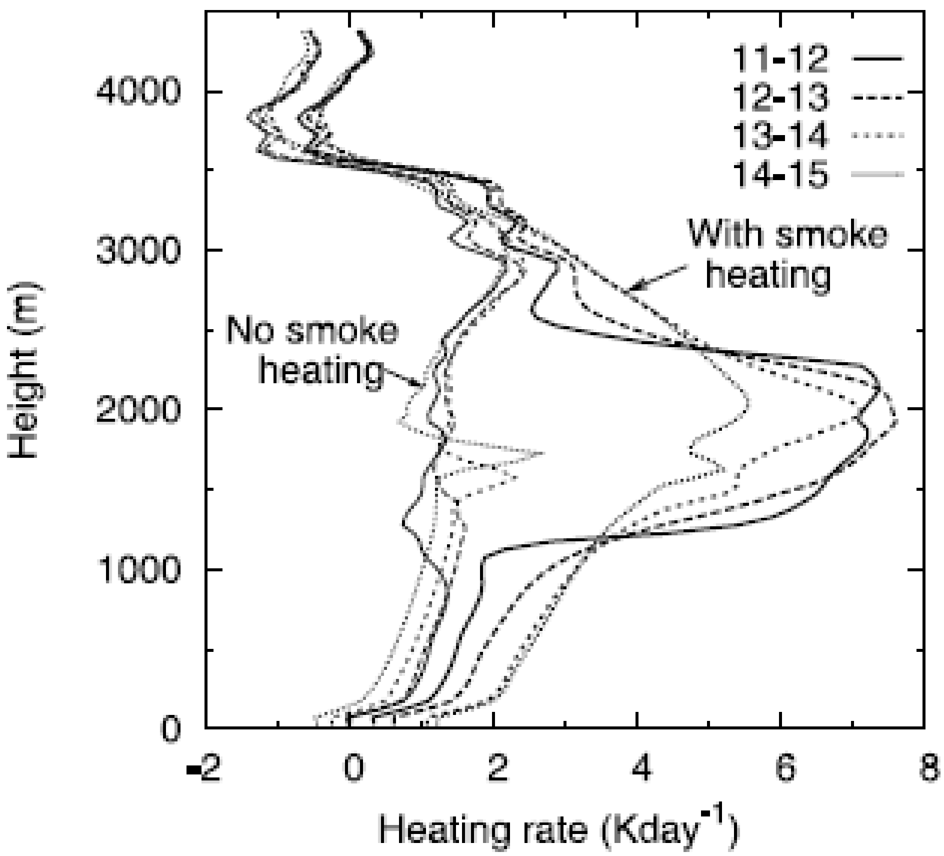

Figure 4 Radiative heating rate profiles in Amazonia simulated with an atmosphere-cloud model.

(from Feingold et al. 2005)

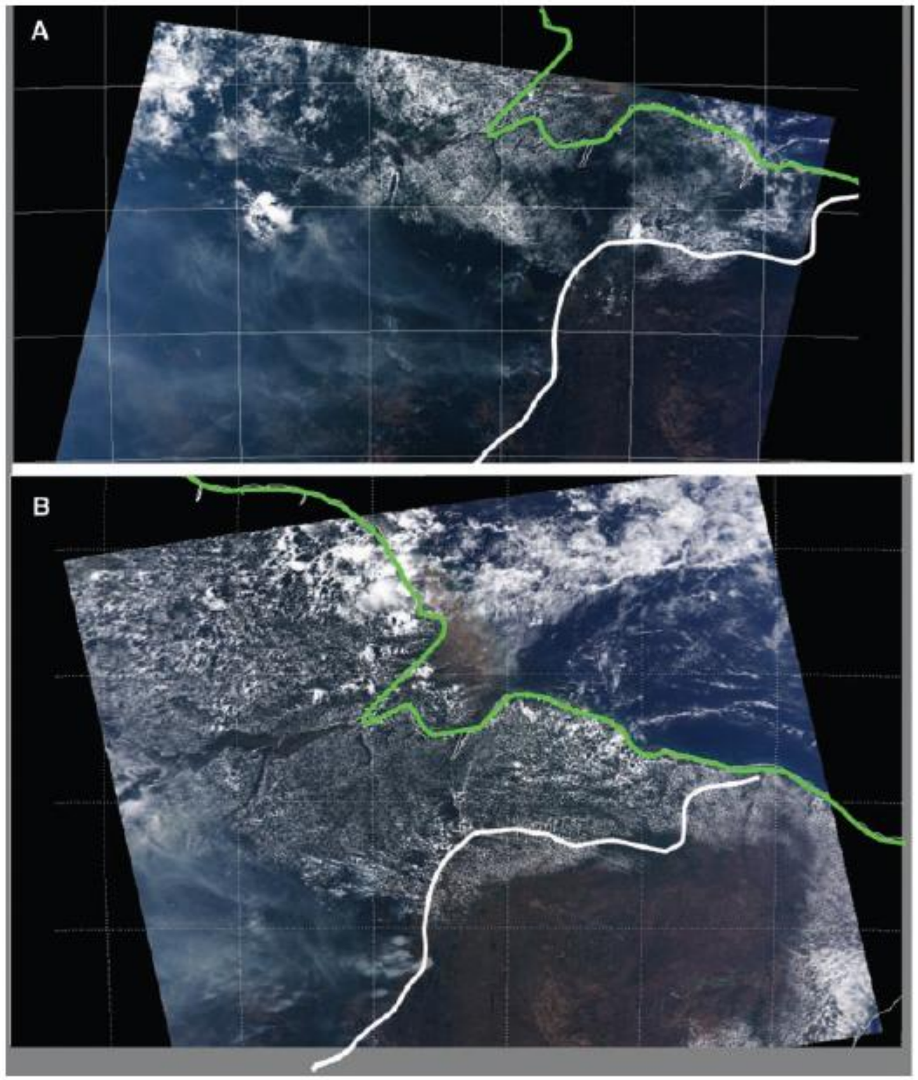

Figure 5 MODIS images of the east Amazon basin on August 11, 2002 showing beginning of cloud formation in the morning (a) and full development of clouds in the afternoon except for the smoke areas. (From Koren et al. 2004).

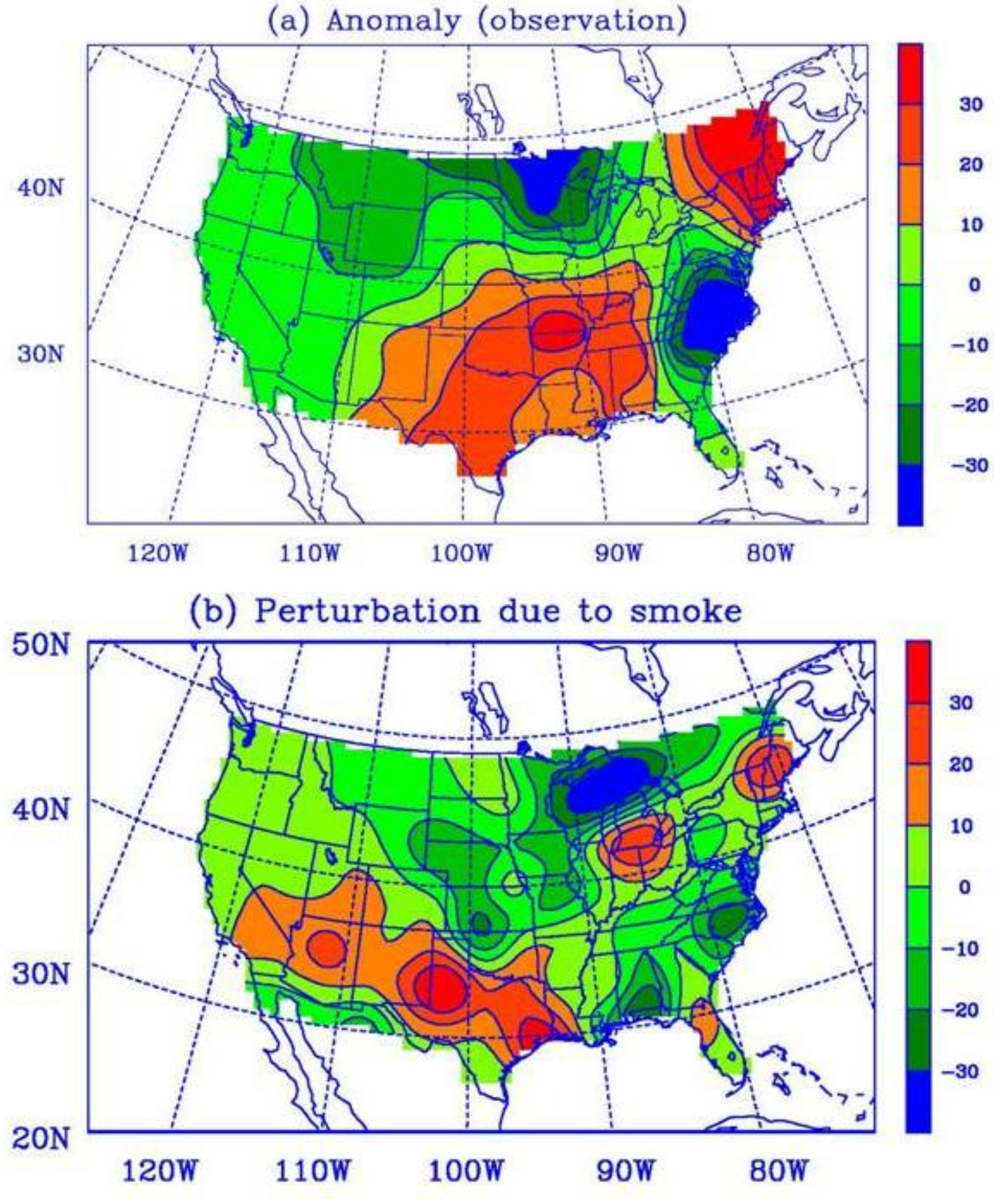

Figure 6 Precipitation anomalies (mm) in July 1988. (a) Observation, and (b) Difference between the regional climate model simulations with and without smoke particles. (From Liu 2005)

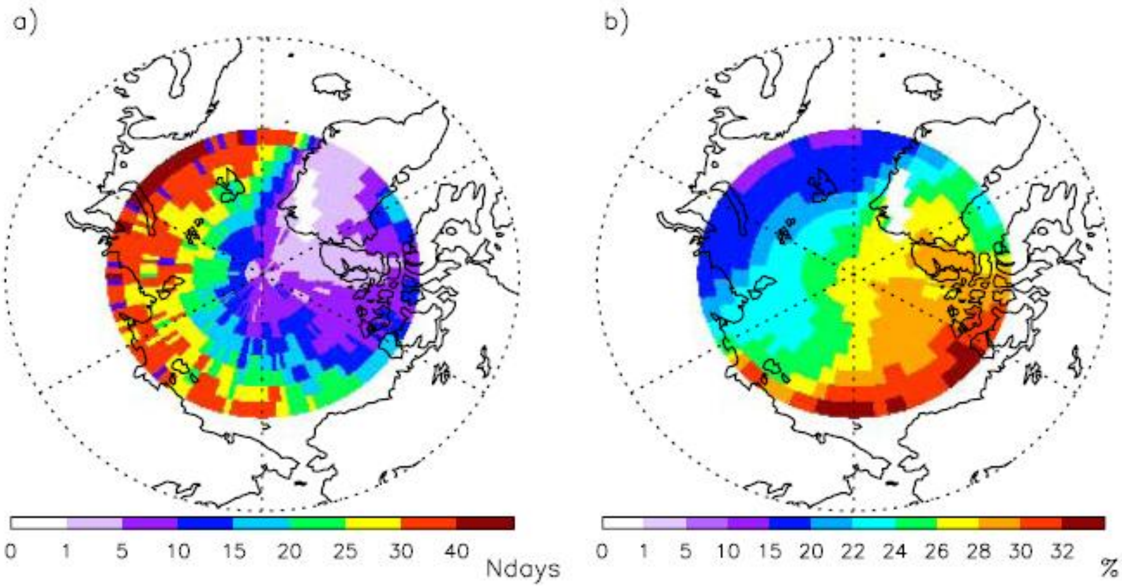

Figure 7 Role of black carbon from wildfires in Arctic radiative forcing and haze. (a) Number of days during a four-month period with optical depth greater than 0.094 (a characteristic value for Arctic haze events), and (b) contribution of the 2003 Russian fires to the optical depth of these days in percent. (From Generoso et al. 2007).

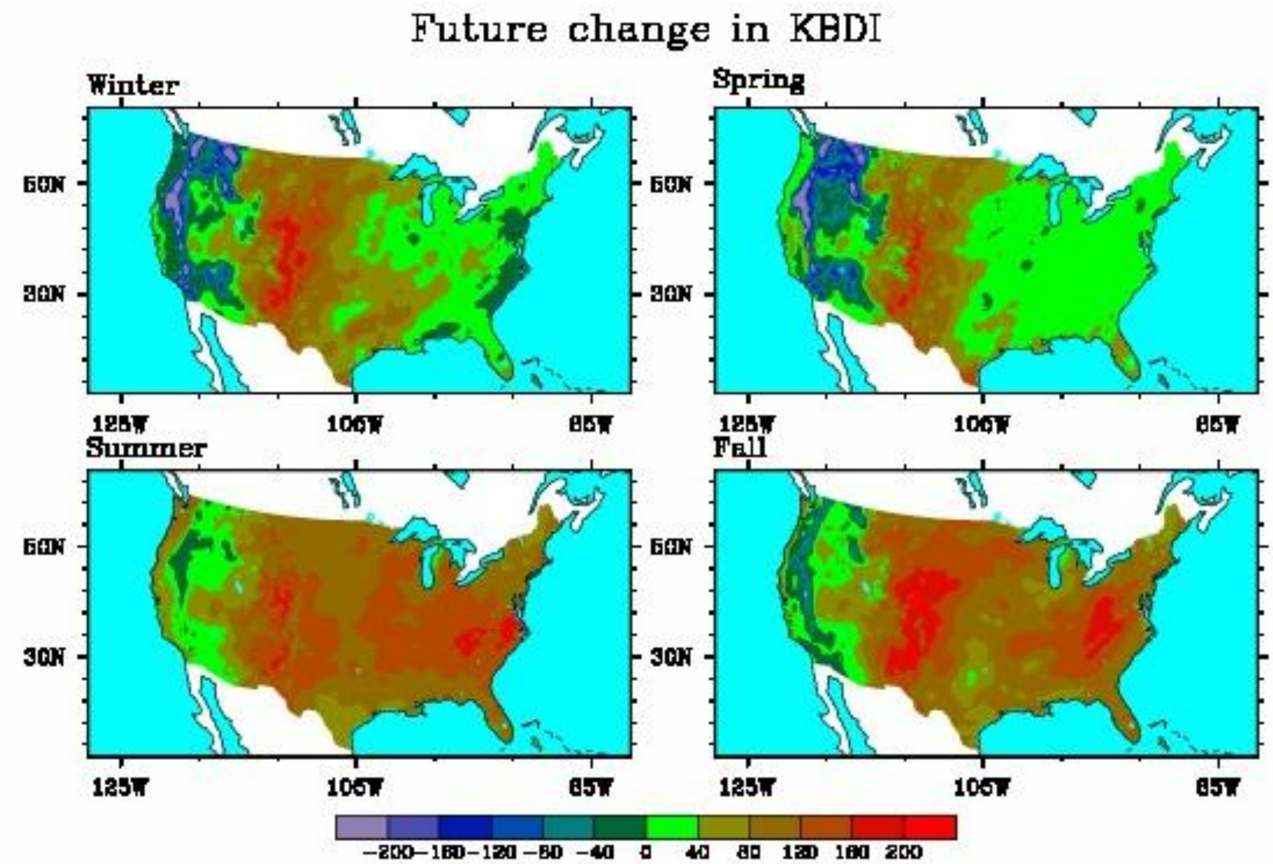

Figure 8 Change in KBDI of North America for winter, spring, summer, and fall seasons between 2041-2070 and 1971-2000 calculated using the data obtained from the NARCCAP. (From Liu et al., 2012).

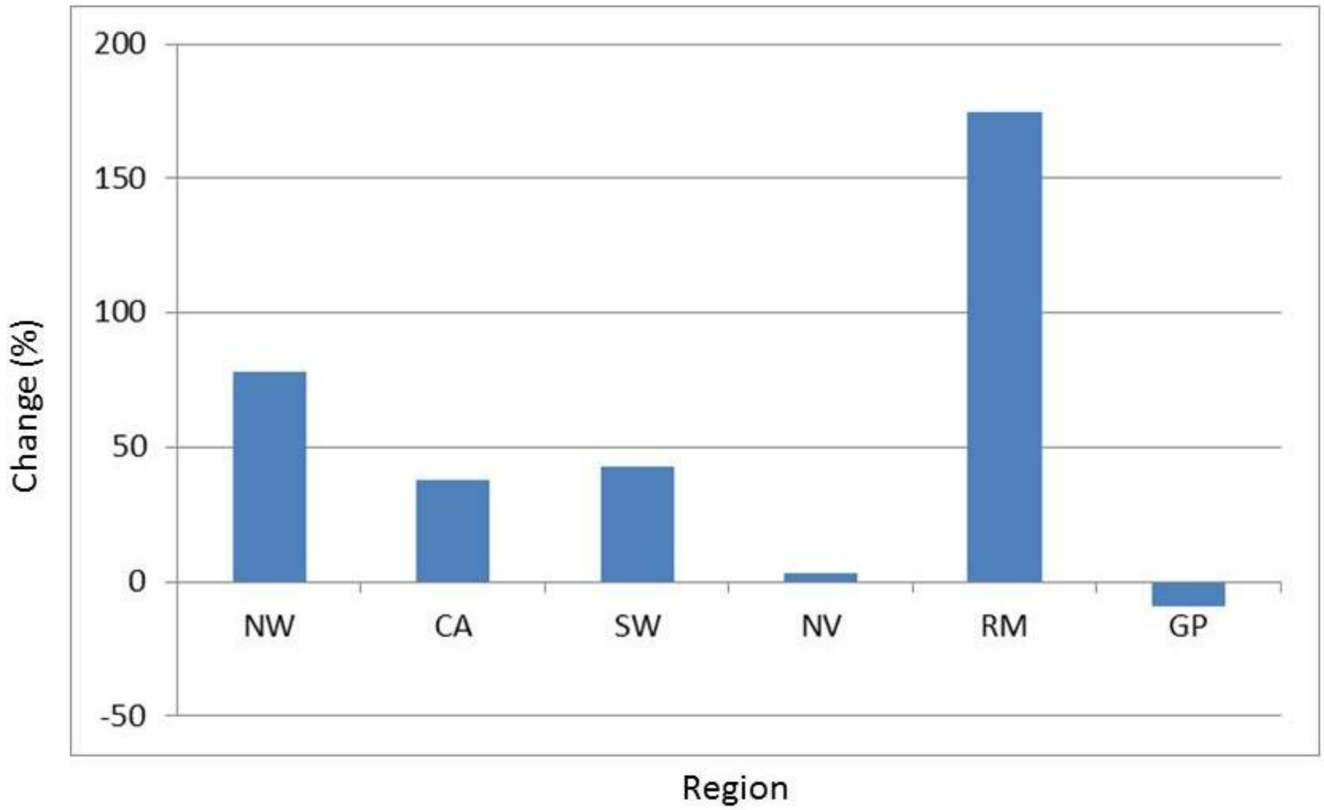

Figure 9 Change rate (%) in burned areas of wildfires from present (1980-2004) to future (2046-2055) in the western United States. The regions are NW (Pacific Northwest), CA (California Coastal Shrub), SW (Desert Southwest), NV (Nevada Mountains /Semi-desert), RM (Rocky Mountain Forest), and GP (Eastern Rocky Mountain / Great Plains. (Redrawing based on the results from Spracklen et al. 2009).

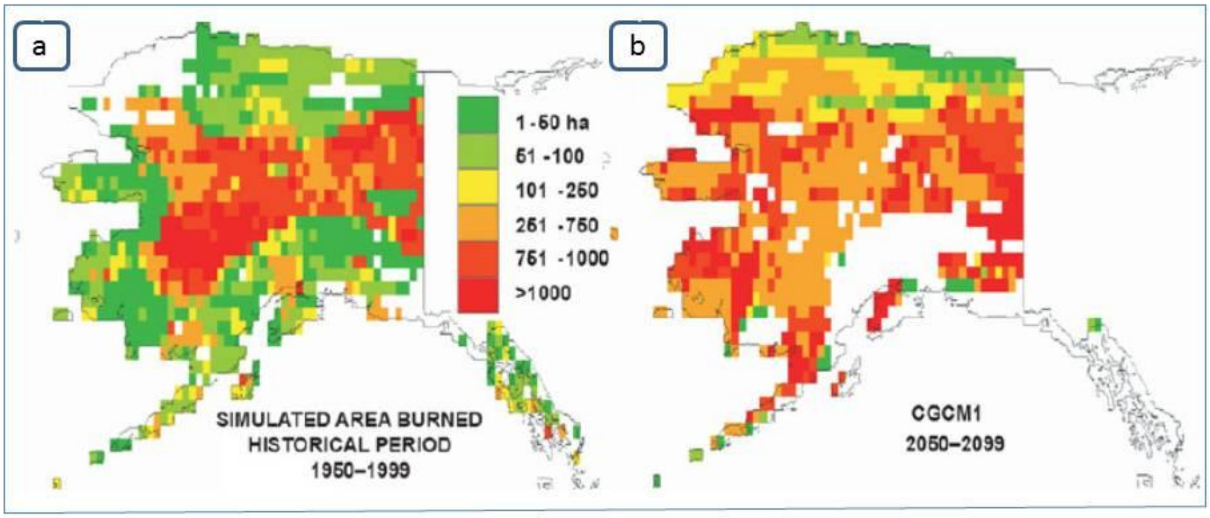

Figure 10 Burned areas in Alaska simulated for 1950-1999 and predicted for 2050-2099. (From Bachelet et al. (2005).

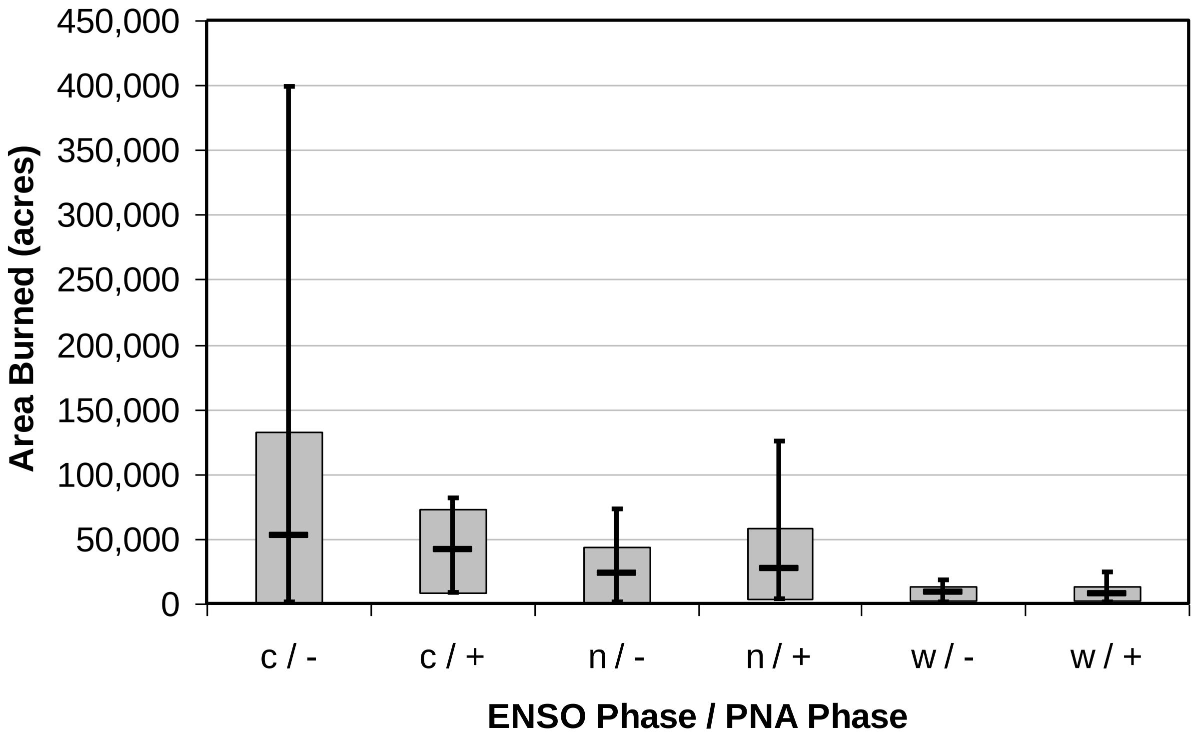

Figure 11: Influence of ENSO and PNA teleconnection on Florida area burned. ENSO phase (c = negative, n = neutral and w = positive) and PNA phase (- = negative and + = positive). Box represents ± 1 standard deviation and whiskers extend from minimum to maximum acres burned (From Goodrick and Hanley, 2009).